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Annual Report

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On the Origin and Evolution of Stellar Chromospheres, Coronae and Winds

Z. E. Musielak

Center for Space Plasma, Aeronomic and Astrophysics Research
University of Alabama in Hunstville

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SUMMARY OF COMPLETED WORK

This grant was awarded by NASA to The University of Alabama in Huntsville (UAH) to construct state-of-the-art, theoretical, two-component, chromospheric models for single stars of different spectral types and different evolutionary status. In our proposal, we suggested to use these models to predict the level of the "basal flux," the observed range of variation of chromospheric activity for a given spectral type, and the decrease of this activity with stellar age. In addition, for red giants and supergiants, we also proposed to construct self-consistent, purely theoretical, chromosphere-wind models, and investigate the origin of "dividing lines" in the H-R diagram. In the following, we list four specific goals for the first year of this project and then describe the completed work.

(1) To calculate the acoustic and magnetic wave energy fluxes for stars located in different regions of the H-R diagram.

(2) To investigate the transfer of this non-radiative energy through stellar photospheres and to estimate the amount of energy that reaches the chromosphere.

(3) To identify major sources of radiative losses in stellar chromospheres and calculate the amount of emitted energy.

(4) To construct self-consistent, stellar wind models based on the momentum deposition by nonlinear Alfvén waves.

Concerning the **first goal**, we have calculated the acoustic wave energy fluxes for chromospherically active stars located in different regions of the H-R diagram (Ulmschneider, Theurer & Musielak 1996). In these calculations, we have used the Lighthill-Stein theory of sound generation recently modified by Musielak et al. (1994). The obtained results clearly show that some previous calculations (Bohn 1984) were incorrect. At the same time, we have developed a new approach to calculate the efficiency of generation of nonlinear transverse (Huang, Musielak & Ulmschneider 1995) and nonlinear longitudinal (Ulmschneider & Musielak 1996) magnetic tube waves. This nonlinear approach supplements our previous analytical treatment of the generation of these waves (see Musielak, Rosner, & Ulmschneider 1989; and Musielak, Rosner, Gail & Ulmschneider 1995). We have used our analytical (for linear waves) and numerical (for nonlinear waves) approaches to estimate the MHD wave energy fluxes for late-type stars located in different regions of the H-R diagram. We are in process of performing these calculations and preparing them for publication in *The Astrophysical Journal.*

As long as the **second goal** is concerned, we have investigated some aspects of propagation of nonadiabatic acoustic waves in the solar atmosphere and modeled chromospheric velocity fields in supergiants. The first project (see Theurer, Ulmschneider & Cuntz 1996) is an expansion of earlier work given by Sutmann & Ulmschneider (1995a,b), which studies the propagation and height evolution of acoustic frequency spectra in the solar atmosphere. Contrary to that earlier work, radiative damping has now been included. Radiation damping modifies the propagation of the wave modes enormously and leads to more realistic chromospheric heating models, determined by the balance of shock wave heating and radiative cooling. For non-adiabatic monochromatic wave excitation, the work confirms a critical frequency $\nu_{cr} \sim 1/25$ Hz, which separates domains of different resonance behaviour.

It is found that for waves of $\nu < \nu_{cr}$, the resonances decay, while for waves of $\nu > \nu_{cr}$ persistent resonance oscillations occur perpetuated by shock merging. On the other hand, excitation with acoustic frequency spectra always produces dynamical chromosphere models with ongoing shock merging. The detailed temperature distributions in the models are found to depend on the shape of the assumed spectra. An important suggestion is made regarding the explanation of the 3 min component observed by Lites et al. (1993) in a low lying iron line, which is not found in the acoustic spectrum generated in the convection zone (Musielak et al. 1994). It is argued that this phenomenon might be a consequence of shock merging in the ca. 600 km height interval between the point of maximum sound generation and the height where the iron line is formed. This would indicate that detailed wave simulations and height–dependent spectral observations may allow to empirically determine the velocity fluctuations in the acoustic wave generation region. If correct, it would allow an important independent check of existing convection and sound generation simulations, which would also be relevant for cases of other stars. In the second project (see Cuntz 1996c), results from recent ab–initio models for the formation and time–dependent behavior of outer atmospheric flows in α Ori (M2 Iab) are given. It is assumed that the atmospheric flows are produced by stochastic shock waves. The wave models show distinct episodes of momentum and energy deposition produced by strong shocks generated by merging of shocks in the stochastic wave field. Sub- and supersonic inflows and outflows are generated at different atmospheric heights as function of the wave parameters adopted. Most importantly, it is found that the flow velocities given by the models encompass the velocity range revealed by the Fe II emission line components given by recent GHRS data (Carpenter & Robinson 1997). This result is evidence that nonmagnetic wave modes are relevant for the heating and dynamics of the outer atmosphere of α Ori and possibly other M-type supergiants as well. In addition, we have investigated the propagation of Alfven waves in the solar coronal holes and in atmospheres of cool giants, and constructed self-consistent wind models; this work is described in details below. The relevant work was also done by Dr. Huang, who investigated the efficiency of energy transfer along magnetic structures (see Huang 1996).

We have addressed the **third goal** by developing a new numerical code that implements a fully consistent solution of the time-dependent statistical rate equations for hydrogen and the thermodynamic and hydrodynamic equations for 1–D flows using the method of characteristics. Carlsson & Stein (1991, 1992, 1995) found that in models of the solar chromosphere, the time-scales for hydrogen ionization and recombination are comparable to or larger than the time-scale for changes of the relevant hydrodynamic quantities. As this effect is of particular importance at low densities and behind shocks, it can be expected that it is also relevant for the outer atmosphere of other types of stars, including giants and supergiants. Noninstantaneous hydrogen ionization largely changes the size of temperature spikes in shock heating models and impacts the general behavior of thermodynamic quantities. As a consequence, it should also affect the formation of important emission lines such as Mg II h, k and Ca II H, K and the position of the basal flux line in the HR diagram, which is often use to assess the relevance of acoustic heating. This work has been done by Dr. Cuntz and the developed code will be applied to calculate radiative losees from stellar chromospheres.

Finally, to address the **fourth goal**, we have constructed first fully theoretical and self-consistent wind models based on the momentum deposition by nonlinear Alfven waves. The first results from this self-consistent study of Alfven waves for the time–dependent single–fluid magnetohydrodynamic (MHD) solar wind equations have been performed by using a modified version of the ZEUS MHD code (see Ong, Musielak, Rosner, Suess & Sulkanen 1997). The wind models we examine are radially symmetric and magnetized; the initial outflow is described by the standard Parker wind solution. Our study focuses on the effects of Alfvén waves on the outflow and is based on solving the full set of the ideal nonlinear MHD equations. In contrast to previous studies, no assumptions regarding wave linearity, wave damping, and wave-flow interaction are made; the models thus naturally account for the backreaction of the wind on the waves, as well as for the nonlinear interaction between different types of MHD waves. Our results clearly demonstrate when momentum deposition by Alfvén waves in the solar wind can be sufficient to explain the origin of fast streams in solar coronal holes; we discuss the range of wave amplitudes required to obtained such fast stream solutions. The developed numerical code is being currently used to construct self-consistent wind models for cool giants and supergiants.

Additional work relevant to the proposed research

In addition to the reseacrh described above, we have also worked on the observed rotation-activity relation, which eventually be used to estimate the number of fluxes tubes on the surface of different late-type stars. It has now been widely recognized that besides acoustic heating which is probably responsible for providing the basal atmospheric heating component, magnetic heating is the basic ingredient in the atmospheric energy balance of most types of stars. Magnetic heating is extremely relevant in stars with high rotation rates, which are also found to have an enhanced level of chromospheric activity. It is a major objective of this program to construct models for this type of stars. This can be done by calculating time–dependent longitudinal flux tube models using realistic atmosphere models and up-to-date computations for the magnetic energy generation. Energy losses in important chromospheric lines such as Mg II will be simulated using the methods developed by Ulmschneider (1994) and Hünerth & Ulmschneider (1995). Ultimately, these models can be used to evaluate empirically deduced rotation—activity relations as given by Rutten (1986) and Schrijver et al. (1989). In addition, the models can also be used to study the evolution of solar–type activity in well–studied individual stars as e.g. β Hyi (G2 IV) (Dravins et al. 1993), which evolved apart from the main sequence. This work has been primarily done by Dr. Cuntz. He also presented one review paper (see Cuntz 1996a) describing recent observational and theoretical results concerning the physics of magnetic and nonmagnetic chromospheric heating as inferred from IUE, HST-GHRS and ROSAT data, and one contributed paper (Cuntz 1996b) describing results from UV spectroscopy for α Ori (M2Iab) based on data from HST-GHRS and IUE; the results have some implication regarding the atmospheric heating mechanisms.

The results described above have been obtained by the P.I. (Dr. Z. E. Musielak), Co-I's (Drs. R. Rosner and P. Ulmschneider), one senior research associate (Dr. M. Cuntz, who joined UAH in Jan. 1996), one junior research associate (Dr. P. Huang, who joined UAH in Jan. 1996 and left in May 1996 to work for industry), and two graduate students in physics (Mr. K. K. Ong and V. Korman). Dr. Cuntz has devoted all his time to work on the project. He has been closely working with the P.I. and Dr. Ulmschneider, and both graduate students. He also worked with Dr. Huang during her stay at UAH. Dr. Rosner visited UAH in February 1996 and stayed for a week working on the wind acceleration problem. Dr. Ulmschneider visited UAH in Sept./October 1996 and stayed at UAH for 3 weeks working on the wave generation and propagation problem. Last year Mr. Ong spent three months at the Univeristy of Chicago working with Dr. Rosner on construction of self-consistent and time-dependent stellar wind models. Finally, the P.I. has been working on several problems directly related to the project during the regular academic year when his salary is fully paid by UAH.

As a result of this NASA support, we have completed 12 main and 6 contributed papers (see the list below) and we plan to present several papers at the *Cool Stars Meeting* in Cambridge, MA, in July 1997.

PAPERS RESULTING FROM THIS NASA AWARD

"On the Efficiency of Energy Transfer by Nonlinear Magnetohydrodynamic Waves Propagating Along Magnetic Slabs" Structured Regions of the Solar Atmosphere" Huang, P., *Phys. Plasmas*, 3, 2579-2588 (1996).

"Propagation of MHD Body and Surface Waves in Magnetically Structured Regions of the Solar Atmosphere" Wu, S. T., Xiao, Y. C., Musielak, Z. E., and Suess, S. T., *Solar Phys.*, 163, 291-307 (1996).

"Wave Resonances and Induced Flow Due to Nonlinear Alfven Waves in a Stratified Atmosphere" Stark, B. A., *J. Geophys. Res.*, 101, 15,615-15,628 (1996).

"Acoustic Wave Energy Fluxes for Late-Type Stars" Ulmschneider, P., Theurer, J. and Musielak, Z. E. *Astron. Astrophys.*, in press (1996).

"First Self-Consistent and Time-Dependent Solar Wind Models" Ong, K. K., Musielak, Z. E., Suess, S. T., and Sulkanen, M. E. *Astrophys. J. Letters*, in press (1997).

"Ambiguity in Calculating Reflection Coefficient for Alfven Waves Propagating in the Solar Wind" Krogulec, M., Musielak, Z. E., and Suess, S. T., *J. Geophys. Res.*, submitted (1996).

"A Numerical Study of Nonlinear MHD Body and Surface Waves Using a Finite-Difference Method" Huang, P., *J. Comp. Physics*, submitted (1996).

"On the Generation of Nonlinear Magnetic Tube Waves in the Solar Atmosphere. II. Longitudinal Tube Waves" Ulmschneider, P., and Musielak, Z. E. *Astron. Astrophys.*, submitted (1996).

"Acoustic Wave Propagation in the Solar Atmosphere. IV. Nonadiabatic Wave Excitation with Frequency Spectra" Theurer, J., Ulmschneider, P., & Cuntz, M. *Astron. Astrophys.*, submitted (1996).

"Chromospheric Velocity Fields in α Orionis (M2 Iab) Generated by Stochastic Shocks" Cuntz, M., *Astrophysical Journal Letters*, submitted (1996a).

"Acoustic Wave Propagation in the Solar Atmosphere. V. Analytic Solutions for Adiabatic Wave Excitations" Sutmana, G., Musielak, Z. E., & Ulmschneider, P., *Astron. Astrophys.*, to be submitted (Jan. 1997).

"On the Generation of Flux Tube Waves in Stellar Convection Zones. III. Transverse Tube Waves Driven by Forced Turbulence"
Musielak, Z. E., Rosner, R., Gail, P. H., & Ulmschneider, P. *Astrophys. J.*, to be submitted (Feb. 1997).

CONTRIBUTED PAPERS RESULTING FROM THIS NASA AWARD

"Chromospheric Heating in Late-Type stars: Evidence for Magnetic and Nonmagnetic Surface Structure", Cuntz, M., in *Stellar Surface Structure*, Proc. IAU Symposium 176, eds. K.G. Strassmeier and J.L. Linsky (Dordrecht: Kluwer), p. 393 (1996b)

"Generation of Linear and Nolinear Tube Waves in the Solar Atmosphere" Musielak, Z. E., Rosner, R., and Ulmschneider, P. *Proceedings of the IAU Colloq. No. 153 on Magnetodynamic Phenomena in the Solar Atmosphere - Prototypes of Stellar Activity*, Makuhari near Tokyo, Japan, Eds. Y. Uchida, T. Kosugi and H. S. Hudson, p. 427 (1996).

"Alfven Wave Resonances and Flow Induced by Nonlinear Alfven Waves in a Stratified Atmosphere" Stark, B. A., Musielak, Z. E., & Suess, S. T., in *Solar Wind Eight* in press (1996).

"Effects of Thermal Conduction on the Energy Balance of Open Coronal Regions" Hammer, R., Nesis, A., Moore, R. L., Suess, S. T., and Musielak, Z. E. *Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun*, Eds. R. Pallavicini and A. K. Dupree, in press (1996).

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